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# Comparing the Seismic Collapse Capacity of Steel Moment Resisting Frames with Inclined Columns

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## ABSTRACT

Due to some constructional and architectural issues, the columns of the structure, which play the main load-bearing role in it to transfer imposed loads to foundation, may be forced out of their upright position and run obliquely, or it may even be determined due to a defect in the construction that the column is placed in an inclined manner. As a result, it is necessary to evaluate the effect of the column inclination against seismic excitations. In this research, a 5-story steel moment resisting frame with three spans and considering six scenarios of the column inclination is investigated in OpenSees software by using incremental dynamic analysis (IDA) and plotting fragility curves. The rotation of the columns around the supports is assumed 1 degree. Also, the influence of deteriorations of stiffness and strength is considered for modeling the studied samples exactly. Finally, the collapse capacity of the mentioned steel frames is assessed under the influence of far-fault ground motions probabilistically. Findings of this paper show that the M6I25 model has more collapse capacity than other samples under the studied records, and it is determined that at the statistical level of 50%, the aforementioned collapse capacity is increased 14% in comparison with the main model. Also, based on the spectral acceleration of 0.7 g, the collapse probability of the M6I25 model is 50.8%.

**Keywords: Steel moment frame; Deterioration; Inclined column; Incremental dynamic analysis (IDA); Fragility curve**

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## 1. INTRODUCTION

Today, the architectural and engineering landscape is characterized by the prevalence of buildings featuring intricate, conical, and slanted designs, reflecting the advancements in technology and the skill of professionals in the construction sector. The traditional method of connecting beams to columns at right angles has evolved, particularly with the introduction of inclined columns in many modern structures. These columns serve as critical components, responsible for transferring both vertical and lateral loads to the foundation. Furthermore, conventional column

designs can be adapted to include inclined columns, which introduces additional bending moments due to the load being applied at a distance from the column's section. Consequently, the effective functioning of these columns is crucial for the overall performance and stability of the structures. [1, 2]. Han et al. (2010) assessed the performance of the concrete-filled steel tubular (CFST) stub columns with different cross-sections in an inclined and vertical manner [3]. Lam et al. (2012) investigated the performance of inclined steel pipes filled with concrete against axial load. The axial load capacity of the box-shaped inclined column decreased by 7.9% when the angle of deviation increased to 9 degrees [4]. Hansapinyo et al. (2018) studied the inclined column on the first floor and it showed that if the column of the first floor is inclined, compared to a structure where all the beams and columns are vertical, these inclined columns will increase the stiffness of the structure compared to the completely upright columns [5]. Zhang et al. (2021) examined the seismic performance of steel-reinforced concrete inclined column transfer structure (SRC-ICTS). The results regarding seismic behavior suggest that enhancing the axial force ratio can lead to an increase in the ultimate bearing capacity; nevertheless, the energy dissipation capability and ductility of the SRC-ICTS diminish as the axial force ratio becomes excessively high. It is recommended that the axial force ratio of SRC-ICTS should be maintained below 0.4 to ensure satisfactory seismic performance [6]. Tao et al. (2022) investigated the behavior of the oblique cantilevered steel reinforced concrete structure (OCSRCS). The findings of this research indicated that the Self-balancing and Self-supporting Method implemented for the OCSRCS effectively guarantees construction safety. Furthermore, it offers valuable insights for the development of large-scale OCSRCS in engineering projects [7]. The study conducted by Abramczyk et al. (2023) focused on assessing the influence of the inclination of girders and columns on the effort and stability of flat bar frames. The mentioned research provided an explanation of a unique approach to use inventive transverse systems of flat bar frames as structures that induce elastic shape transformations in folded sheets, resulting in ruled shell roof coverings [8]. Also, investigating the seismic collapse capacity of steel moment resisting frames (SMRFs) under the effect of earthquakes with different natures is one of the most important challenges of structural and earthquake engineers. Although structural damages can be evaluated at different levels, the collapse of buildings is considered one of the unfortunate events in the construction industry, where the loss of life and money reaches its highest possible value. The collapse of buildings under an earthquake appears as local and global collapse. In local collapse, usually, one or more gravity-bearing members of the structure are removed due to damage from the system and a part of the structure collapses. Local collapse can cause the entire structure due to the transfer of damage from one element to another one [9]. In global collapse, the entire structure loses its functionality. Sidesway collapse is a type of global collapse in which the drift of one or more stories compared to other stories becomes so large that under the effect of the secondary moment caused by the weight of the building (P-Δ effect), the structure is practically able to return to its normal state. It will not balance itself and a global collapse will occur [10]. During the past years, various methods and attitudes have been presented to study the seismic collapse capacity of structures. In the past studies, accurate energy dissipation models based on experimental researches were not presented and most of them were based on the analysis of simple models with one or more degrees of freedom [11]. Adam et al. (2004) investigated the effect of P-Δ on the collapse of multi-degree-of-freedom structures by transforming them into an equivalent one-degree-of-freedom structure [12]. Miranda and Akkar (2003) investigated the dynamic instability of simple structural systems without considering the resistance reduction models of structural elements [13]. Williamson (2003) evaluated the damage to structural systems under earthquakes by considering the effect of P-Δ [14]. Bernal et al. (2006) assessed the instability of structural systems under near-fault earthquakes and presented collapse spectra [15]. In the last two decades, to consider the factors affecting the seismic collapse capacity of structures, efforts have been focused on considering the models of stiffness and strength deterioration of the elements. Rahnama and Krawinkler (1993) have developed the principles of stiffness and strength deterioration of structural elements under cyclic loads [16]. Ibarra et al. (2005) and Lignos and Krawinkler (2009) provided data for modeling steel elements based on the Ibarra-Medina-Krawinkler model (IMK) [17-19]. Lignos and Krawinkler (2010) introduced reduction parameters

pertinent to the Inelastic Moment Capacity (IMK) for steel box columns constructed from hollow structural sections (HSS) subjected to varying axial forces [20]. Extensive research has been conducted to assess the performance of Special Moment Resisting Frames (SMRFs), which will be elaborated upon subsequently. Sadeghi et al. (2022) examined the fragility curves of SMRFs when impacted by a vehicle colliding with one of their columns, while another study by the same authors (2021) optimized the weight of SMRFs in response to impact loads through the application of evolutionary algorithms [21, 22]. Additionally, Saberi et al. (2021) analyzed the implications of progressive collapse on high-rise steel structures featuring different bracing configurations [23]. Razmkhah et al. (2021) and Kouhestanian et al. (2023) explored the influence of aftershocks, as well as plan and height irregularities, assessing the reduction in structural capacity resulting from these factors, including torsional irregularities and the presence of a soft story [24, 25]. Furthermore, Saberi et al. (2022) investigated the impact of fire on the behavior of steel structures, revealing that variations in specific factors lead to changes in damage modes, particularly concerning the thickness of connections under thermal loading conditions [26]. Sadeghi et al. (2024) investigated the impact of the pounding effect between two adjacent SMRFs featuring intermediate ductility, specifically focusing on configurations with 2 and 5 stories under seismic loading. The results derived from the Kriging meta-model indicated a 65% increase in failure probability for the frames of unequal height compared to those of equal height [27].

By reviewing the past technical studies, it is found that the incremental dynamic analysis (IDA) and fragility curves of SMRFs with inclined columns have not been investigated so far. Therefore, in this study, the 5-story SMRF with three bays with different scenarios of inclined columns is evaluated by IDA and fragility curves. Six scenarios of inclined columns are considered in this research. It is noted that for modeling of SMRFs with inclined columns, the influence of stiffness and strength deterioration is assumed according to the results of the experimental models of IMK [18] and the seismic collapse capacity of the mentioned models is analyzed in OpenSees software [28] under the effect of far-fault earthquake records probabilistically. The necessity for the current research project is evident as it has been noted through various design investigations that inclined columns in buildings have a significant impact on earthquake forces. The findings of this study reveal that a specific inclination of oblique columns in buildings can make them susceptible to wind and earthquake force phenomena, resulting in high dynamic loads that dictate the design process. This research is poised to spark interest in utilizing inclined columns in the lateral load resistant design of SMRFs, shedding light on their potential benefits and challenges. The study is anticipated to highlight the crucial role that the inclination of oblique columns plays an important role in enhancing the lateral load resisting capacity of steel structures, emphasizing its importance in structural design considerations. Finally, by reviewing the obtained results of collapse probabilities of mentioned SMRF with different scenarios of oblique columns, the suitable configuration of SMRF with inclined columns is specified and proposed.

## 2. METHODOLOGY

### 2.1. Modelling Verification

At first, it is necessary to verify the modeling procedure with the results of drift values of an experimental sample [29] are compared with the values obtained from OpenSees software. The experimental sample is actually a four-story two-span SMRF with a scale of a 1:8 from the main building located in the city of Los Angeles in the United States of America. This structure is designed based on the IBC standard [30]. In the modeling of this sample, the W27X102 and W21X93 beam sections were utilized in the first and second stories, while the W24X131 and W24X76 column sections were employed in the third and fourth stories. A992 steel Grade 50 was the material chosen for all components in this particular model. The lateral loads applied on the first three stories were set at 4600 N, while the fourth story had a load of 5300 N (1200 kips). Also, the gravity loads are considered based on leaning P −Δ column. To compare the outcomes from the experimental and software models, load-drift curves were created for both models, as depicted in Figure 1. The analytical model utilized the Uniaxial Materials Command to define the steel materials, specifically employing Steel02 materials with isotropic hardening. These materials were selected due to their ability to account for rupture and drop resistance conditions.

Additionally, Fiber Section was used to define the beam and column cross-sections in OpenSees, allowing for the application of various material characteristics to each element's cross-section. In this study, the Nonlinear Beam-Column Element command was utilized to define the elements, as the analysis conducted was non-linear. This command effectively models the elements in a non-linear manner. Additionally, it is employed to distribute the inelastic effects throughout the model. To accurately represent the material behavior, the experimental sample was modeled in OpenSees software by carefully selecting and examining the behavior model. The modeling sample was subjected to both gravity and lateral loads exactly like an experimental sample. Finally, the drift values obtained from the experimental results and modeling in OpenSees software coincide with each other based on Figure 1. As a result, the maximum difference of roof drift between the modeled sample and the experimental sample is 20% versus PGA of 1 g.

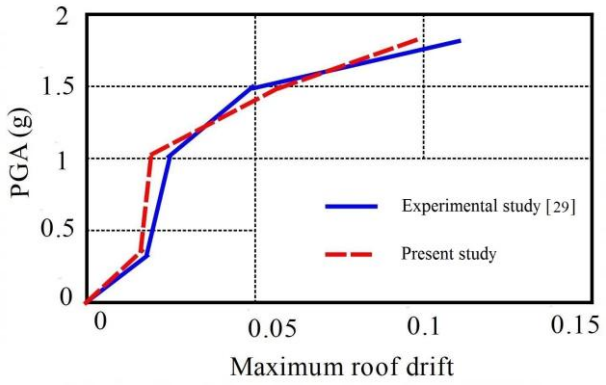
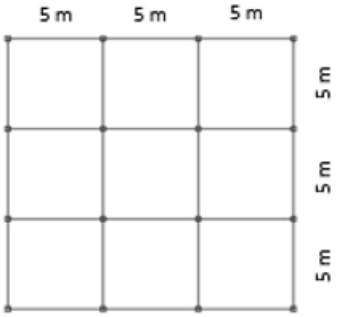



**Figure 1.** The comparison of drift values of different PGA in experimental and present study.

## 2.2. Modelling process

Then for achieving the goal of this research, the 5-story SMRF with three bays and height of each story is 3 m with different scenarios of inclined columns is modeled and then the behavior and collapse capacity of mentioned SMRFs is investigated by using IDA and fragility curves under far-fault earthquake excitations. The goal of this research is to present the probabilistic framework for specifying the collapse probabilities of mentioned frames. In this study, SMRF samples with an intermediate ductility are designed in ETABS [32] in a very high-risk area on soil type D based on ASCE07 [33] and AISC-360 [34]. The effect of $p-\Delta$ has been employed in the design of these models. In the following, dead and live loads of the stories are 600 kg/m2 and 200 kg/m2, respectively. Yield strength and modulus of elasticity are considered to be 275 MPa and 200000 MPa. Figure 2 indicates the 3D model, joint plan of the SMRFs, 2D SMRF with rotational springs and panel zone. To conduct nonlinear analyses, the designed cross-sections of SMRF are specified in Table 1. To consider the P-Δ effect caused by gravity loads in the tributary plan area of the SMRF, the models incorporate the Corotational Coordinate Transformation [35]. In order to solve the equations of motion for SMRFs experiencing earthquake ground motion, the Newmark method with constant acceleration is employed. Also, neglecting buckling in columns is considered in this research.

a)

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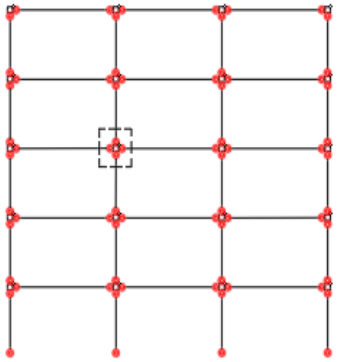
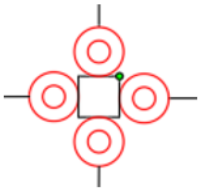




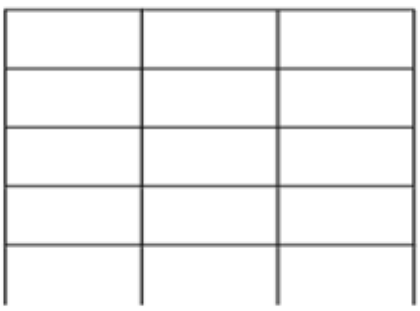
**c)** **d)**

**Figure 2. a)** Details of 3D model, **b)** Joint plan of the 5-story SMRFs, **c)** 2D elevation of the models studied with rotational springs and **d)** Schematic configuration of panel zone.

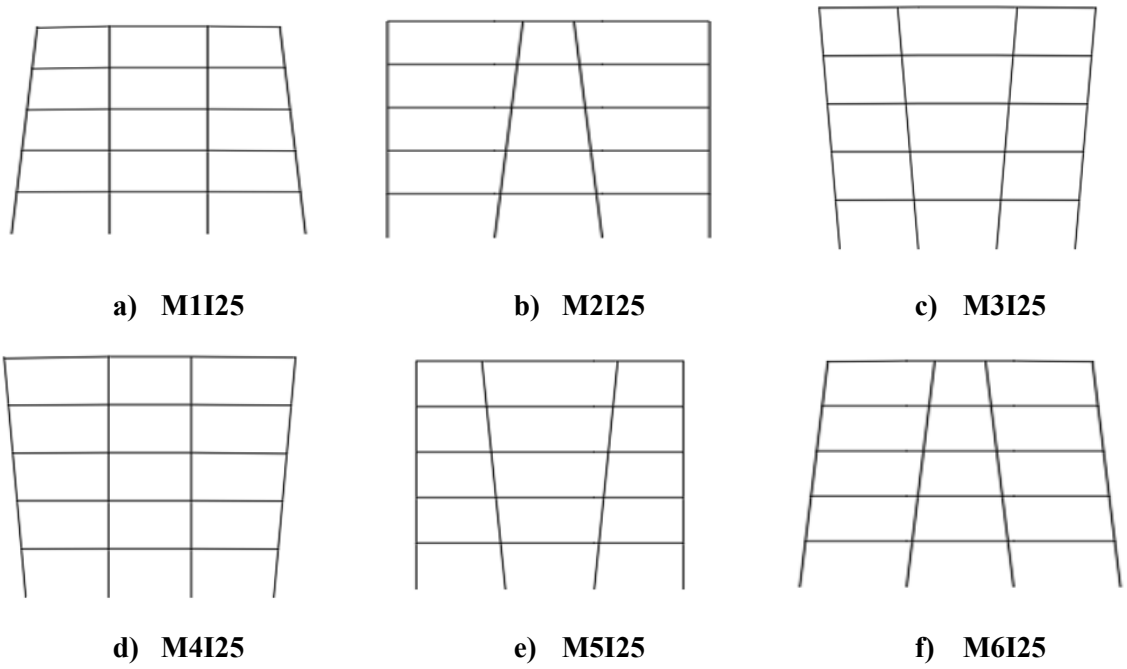
**Table 1.** Cross-sections of the beams and columns of the 5-story SMRF.

| Story | Element | Cross-section |
|---|---|---|
| 1 | Beam | **IPE400** |
| | Column | **HSS 300x300x12** |
| 2 | Beam | **IPE400** |
| | Column | **HSS 300x300x12** |
| 3 | Beam | **IPE400** |
| | Column | **HSS 280x280x12** |
| 4 | Beam | **IPE360** |
| | Column | **HSS 260x260x12** |
| 5 | Beam | **IPE360** |
| | Column | **HSS 260x260x12** |

Next, various frames with side, corner and middle columns have been developed around the place of connection to the ground. In order to evaluate the role of the rotation of the columns, the middle frame of this structure was selected and the deviation of the columns on the roof floor was the criterion of the rotation. For this purpose, the deviation of the columns on the roof floor has been chosen as 25 cm. The deviation values of 25 cm for a 5-story SMRF with a height of 3 meters are equivalent to the rotation of the columns around the supports by 1 degree. Figure 3 shows the desired SMRFs named MxI25. M denotes Model, x is the number of the model, I denotes the inclined column and the number 25 shows the amount of deviation in the roof of the frame.



**a) Main Model**



a) M1I25 b) M2I25 c) M3I25

d) M4I25 e) M5I25 f) M6I25

**Figure 3.** Details of the models studied for evaluating the role of inclined columns on seismic collapse capacity.

### 2.3. Details of modelling IMK and Panel zone

The evaluation of collapse capacity of SMRFs needs the prediction of strength and stiffness deterioration factors of structural components under the effect of ground motions. Ibarra et al. (2005) offered IMK model to evaluate the performance of structural components of SMRFs. The factors of this model require enough experimental data for used materials. In the following, a database for modeling IMK is proposed by Lignos and Krawinkler (2007). The hysteretic responses of different cross-sections of beams and columns were calibrated with regard to more than 300 experimental samples to guess the deterioration factors [36, 37]. The strength and stiffness deterioration factors for H beams with a depth of less than 533 mm can be expressed based on Equations 1 to 3.

$$\theta_p = 0.0865\left(\frac{h}{t_w}\right)^{-0.365}\left(\frac{b_f}{2t_f}\right)^{-0.140}\left(\frac{L}{d}\right)^{0.340}\left(\frac{C_{1Unit}d}{533}\right)^{-0.721}\left(\frac{C_{2Unit}Fy}{355}\right)^{-0.230} \quad (1)$$

$$\theta_{Pc} = 5.63\left(\frac{h}{t_w}\right)^{-0.565}\left(\frac{b_f}{2t_f}\right)^{-0.800}\left(\frac{C_{1Unit}d}{533}\right)^{-0.280}\left(\frac{C_{2Unit}\cdot Fy}{355}\right)^{-0.430} \quad (2)$$

$$\Lambda = \frac{Et}{My} = 495\left(\frac{h}{t_w}\right)^{-1.34}\left(\frac{b_f}{2t_f}\right)^{-0.595}\left(\frac{C_{2Unit}Fy}{355}\right)^{-0.360} \quad (3)$$

For HSS columns with $275 \le F_y \le 500$ MPa and $18 \le \frac{D}{t} \le 100$, the strength and stiffness deterioration factors are presented based on Equations 4 to 6 [31].

$$\theta_p = 0.614\left(\frac{D}{t}\right)^{-1.05}\left(1-\frac{N}{N_y}\right)^{1.18}\left(\frac{CF_y}{380}\right)^{-0.11} \quad (4)$$

$$\theta_{pc} = 13.82\left(\frac{D}{t}\right)^{-1.22}\left(1-\frac{N}{N_y}\right)^{3.04}\left(\frac{CF_y}{380}\right)^{-0.15} \quad (5)$$

$$\Lambda = \frac{E_t}{M_y} = 3012\left(\frac{D}{t}\right)^{-2.49}\left(1-\frac{N}{N_y}\right)^{3.51}\left(\frac{CF_y}{380}\right)^{-0.20} \quad (6)$$

A rectangle made of eight really stiff elastic beam-column elements with a rotational spring is indicated as panel zone with trilinear behavior of rotational springs. Equations 7 to 9 are presented for panel zone.

$$V_y = 0.55\, F_y d_c t_p \quad (7)$$

$$V_p = V_y\left(1 + \frac{3b_c t_{cf}^2}{d_b d_c t_p}\right) \quad (8)$$

$$\gamma_y = \frac{F_y}{\sqrt{3}G} \quad (9)$$

$$\gamma_p = 4\gamma_y \quad (10)$$

### 2.4. Details of the earthquake records studied

In this study, seven records are selected based on FEMA P 695 [38] for conducting nonlinear dynamic analyses. These records are considered as far-fault ground motions. In the following, it is noted that IDA has been performed with small and controlled steps. According to FEMA P 695, to reduce the dispersion of the results, these records are first scaled to the peak velocity of the accelerogram. Also, in the current research, the spectral acceleration of all records in the period of the first mode of the structure (Sa (T1, 5%)) was scaled to one to reduce the dispersion of the results. In this study, IDA is done and IDA curves are plotted. In the following, for calculating the seismic collapse capacity, fragility curves are obtained for SMRFs with different scenarios of inclined columns. Table 2 indicates the details of the selected earthquakes.

**Table 2**. Details of the selected earthquakes.

| ID No. | Date | Event | Station | Magnitude ($M_w$) | PGA[1] (g) | PGV[2] (cm/s$^2$) |
|---|---|---|---|---|---|---|
| **1** | 1994 | Northridge, CA | Beverly Hills-Mulhol | 6.7 | 0.42 | 59 |
| **2** | 1994 | Northridge, CA | Canyon Country-WLC | 6.7 | 0.41 | 43 |
| **3** | 1999 | Duzce, Turkey | Bolu | 7.1 | 0.73 | 56 |
| **4** | 1999 | Hector Mine, CA | Hector | 7.1 | 0.27 | 29 |
| **5** | 1979 | Imperial Valley, CA | Delta | 6.5 | 0.24 | 26 |
| **6** | 1979 | Imperial Valley, CA | El Centro Array # 11 | 6.5 | 0.36 | 35 |
| **7** | 1995 | Kobe, Japan | Nishi-Akashi | 6.9 | 0.50 | 37 |

[1] Peak ground acceleration
[2] Peak ground velocity

## 3. RESULTS AND DISCUSSION

6IDA is a probabilistic approach for analyzing the performance of structures under the effect of ground motions. In this research, the performance of SMRFs with vertical and inclined columns are evaluated under 7 far-fault earthquake records by using IDA, the results are obtained, and IDA curves are plotted according to Figures 4 to 10. Based on these Figures, the red dot in IDA curves indicates the minimum of the spectral acceleration that causes SMRFs to collapse.

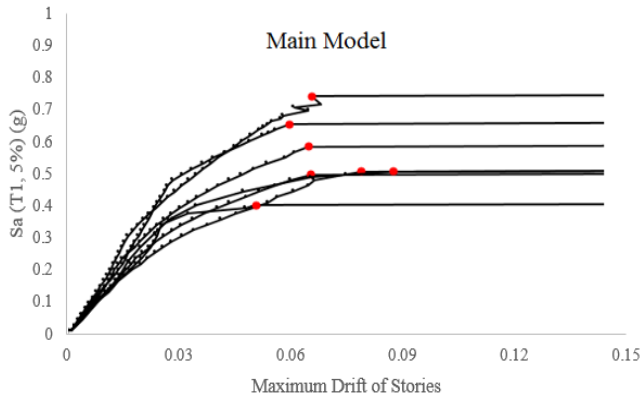



**Figure 4.** IDA curves of Main Model

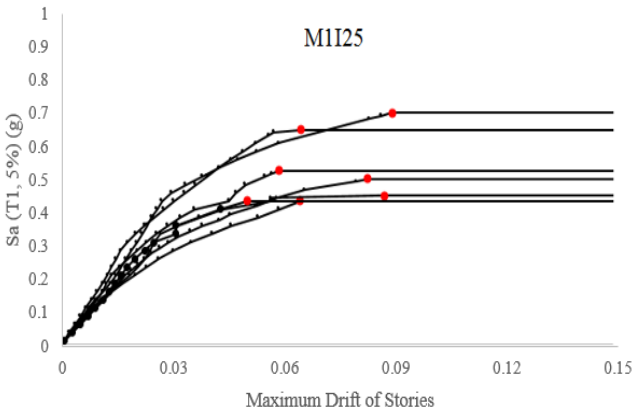



**Figure 5.** IDA curves of M1I25 Model

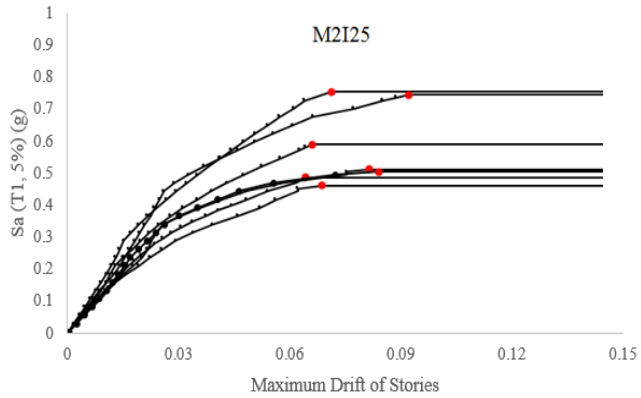



**Figure 6.** IDA curves of M2I25 Model

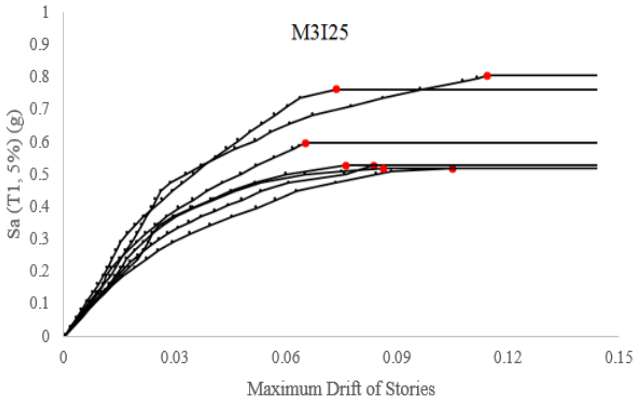



**Figure 7.** IDA curves of M3I25 Model

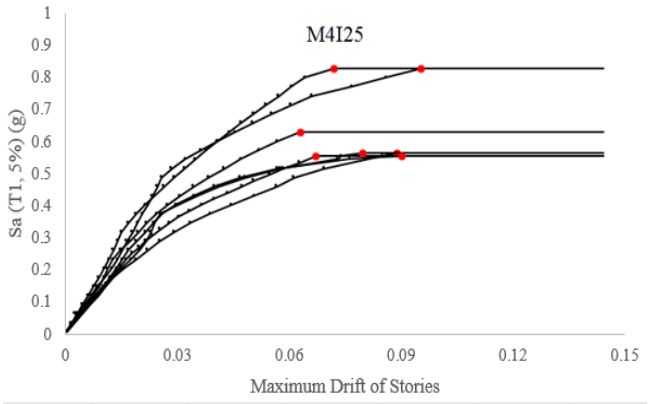



**Figure 8.** IDA curves of M4I25 Model

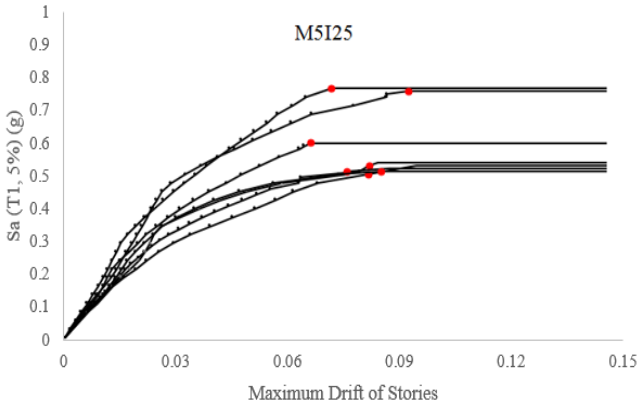



**Figure 9.** IDA curves of M5I25 Model

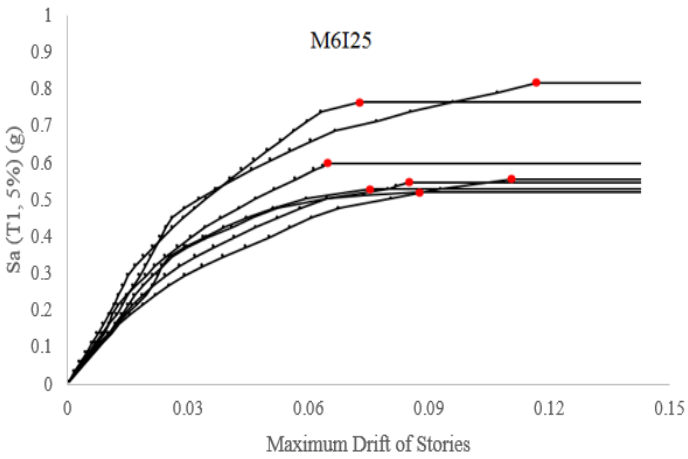



**Figure 10.** IDA curves of M6I25 Model

In this paper, to achieve fragility curves with considering IDA curves, the statistical methods are performed and then fragility curves for 5-story SMRF with and without inclined columns are presented in Figure 11. Finally, the probabilistic evaluation is done to calculate the seismic collapse capacity of the SMRFs by using fragility curves.

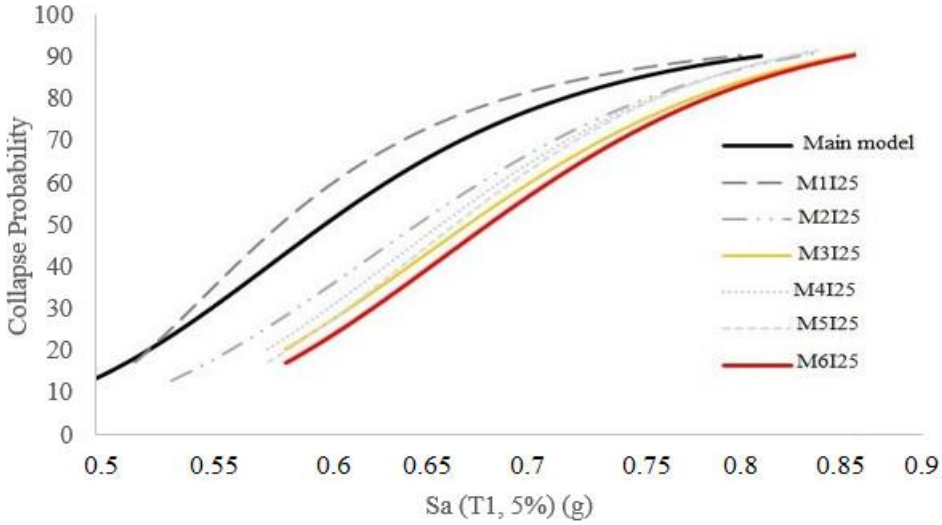



**Figure 11.** Fragility curves of steel frames with and without inclined columns.

According to Figure 11, the seismic collapse capacity of the M3I25 and M6I25 models has been reduced more compared to the main model. Based on Table 3, the collapse capacity of the main model has been compared with the M6I25 model under far-fault records, which has provided better results in increasing the seismic collapse capacity.

**Table 3.** Spectral acceleration of main and M6I25 models based on statistical levels.

| Statistical levels | Spectral acceleration of Main Model (g) | Spectral acceleration of M6I25 (g) |
|---|---|---|
| 16% | 0.51 | **0.6** |
| 50% | 0.61 | **0.7** |
| 84% | 0.74 | **0.83** |

Based on Table 4, the values of the contribution seismic mass of the models are compared with each other. The results of this table showed that the greater the contribution to seismic mass, the more damaged the structure is and the more probability collapses. While the lower the contribution seismic mass, the greater the collapse capacity.

**Table 4.** Values of the contribution of seismic mass of the models.

| Model | Contribution seismic mass (ton) |
|---|---|
| Main Model | **752** |
| M1I25 | **792** |
| M2I25 | **768** |
| M3I25 | **712** |
| M4I25 | **752** |
| M5I25 | **736** |
| M6I25 | **704** |

## 4. CONCLUSION

In this paper, the behavior of the 5-story SMRF with vertical and inclined columns (considering six scenarios) is evaluated probabilistically. The collapse capacity of SMRF with different inclined column scenarios is investigated under the effect of far-fault earthquake records. The key results of this research are presented in the following:

- In comparing the role of creating models with inclined columns in the 5-story SMRF with intermediate ductility, it was determined that at the

statistical level of 50%, the collapse capacity of the M6I25 model has increased by 14% versus the main model.

- According to the spectral acceleration of 0.7 g, the collapse probability of the main model is 73% and the M6I25 model is 50.8%, where a 22.8% reduction in the collapse probability was observed.

- The results of the M5I25 model are very close to the results of the M6I25 model. Other models have also reduced the probability of collapse for different spectral accelerations of collapse and the M1I25 model has shown a higher probability of collapse compared to the original model.

- By examining the results of this research, it was found that by designing or implementing inclined columns instead of vertical columns, the seismic collapse capacity of SMRFs can be significantly improved and also the performance levels of structures related to Immediate Occupancy (IO), Life Safety (LS) and Collapse Prevention (CP) can be predicted.

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AUTHORS CONTRIBUTION

This work was carried out in collaboration among all authors.

CONFLICT OF INTEREST

The author (s) declared no potential conflicts of interests with respect to the authorship and/or publication of this paper.

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